Frequency-dependent modulation and coding rates for LTE link adaptation in static conditions

Frequency-Dependent Modulation and Coding Rates for LTE Link Adaptation in Static Conditions

Javier Lorca
Radio Access Networks Innovation
Telefónica I+D
Madrid, Spain
e-mail: franciscojavier.lorcahernando@telefonica.com

Carlos F. López
Joint Research Institute for Signal and Image Processing
Heriot-Watt University
Edinburgh, EH14 4AS, United Kingdom
e-mail: c.f.lopez@hw.ac.uk

***Abstract*—OFDM wireless cellular systems rely on link adaptation in order to match the Modulation and Coding Scheme (MCS) of the transmission blocks with the dynamic channel conditions experienced at the receive side. For simplicity, Long-Term Evolution (LTE) systems consider a single MCS format per codeword, which is optimized according to the average frequency response over the user's allocated bandwidth. When the channel coherence bandwidth is smaller than the user bandwidth, the constituent codeblocks experience significantly different channel responses, thus rendering link adaptation less effective. This paper proposes a frequency-dependent link adaptation mechanism whereby codeblocks are independently assigned different MCS values that can be fine-tuned to the frequency characteristics of the channel. Post-detection SINR values at the receive side are exploited (instead of CQI values), along with horizontal mapping of resources with two variants: direct mapping and diversity mapping. A suitable in-band signaling scheme for the codeblock sizes and modulations is also described. Link-level simulations show moderate increases in median throughput, but significant improvements in instantaneous throughput, for a broad range of SINR conditions. The proposed scheme can be particularly beneficial when very large signal bandwidths are used as foreseen in future 5G cellular systems.**

Keywords—variable rate; MCS; link adaptation; Link-to-System; effective SINR.

I. INTRODUCTION

Link adaptation (LA) in LTE systems aims at matching the transmitted MCS values with the time-frequency channel response experienced at the receiver side. To this end, suitable channel state information is either estimated at the base station (in uplink direction), or at the UE and then reported back to the network (in downlink direction). In both cases, the format for the whole transmission block is selected so as not to exceed a target block error rate at the receive side [1], [2]. The common MCS value employed for the whole transmission block implies that modulation and coding rates only match the *average* channel conditions and not the instantaneous ones, and this can be relevant when the user bandwidth is larger than the channel coherence bandwidth. Although channel variations somewhat provide additional diversity and robustness to detection errors, they also prevent transmissions from being properly matched to the instantaneous channel frequency profiles, particularly when wide user bandwidths are involved.

LA techniques in downlink direction are typically based on reported Channel Quality Indicator (CQI) values, which are coarse-grained indications that cover a wide range of transmission formats. As CQI values are reported back to the network after taking into account the combined effects of channel and receiver impairments, there is no way for the base station to fine-tune the MCS formats so as to match the channel frequency profile with a higher granularity. Even when subband-specific CQI values are reported as a function of frequency [1], the scheduler finally selects a single MCS value to be used for each user and codeword, hence not exploiting the detailed reported frequency information.

An alternative approach may involve reporting post-detection signal to noise and interference ratio (SINR) values, as obtained at the receive side after channel detection and equalization, and letting the base station derive the most suitable MCS format(s) for the codeblocks comprising the encoded transport block. This approach allows higher granularity and finer adaptation to channel variations in the frequency domain. This can be particularly useful when large information blocks are to be transmitted over wide user bandwidths, where all constituent codeblocks so far undergo the same FEC encoding rates and modulation schemes. When the user bandwidth is much larger than the channel coherence bandwidth, LA will only respond to the average channel state information thus impairing detection.

SINR values are better suited for frequency-dependent LA than CQI values. By making SINR values available at the base station side, it is possible to derive effective SINR values through Link-to-System (L2S) techniques, and use them to fine-tune the MCS formats to be employed in each codeblock. To this end, L2S parameters would have to be reported by the users only once e.g. as part of the device capabilities information. The LTE frequency subbands involved in standard CQI reporting mechanisms are fixed and not related to the actual codeblock sizes, thus frequency-dependent CQI values cannot be translated into codeblock-dependent MCS formats. In contrast, effective SINR values allow the codeblock formats to be matched with the actual frequency profiles experienced by each of them. A horizontal resource mapping procedure is also proposed which contrasts with the standard vertical mapping employed by LTE, hence letting the LA mechanism better match the codeblock sizes and modulations with the different channel responses.

The rest of the paper is organized as follows. Section II describes the proposed frequency-dependent link adaptation mechanism. Section III describes a possible in-band signaling scheme for the resulting codeblock sizes and modulations. Section IV contains simulation results and discussions, and finally Section V is devoted to conclusions.

II. Frequency-Dependent Link Adaptation Procedure

Let us consider an LTE-like transmission system, comprising a FEC encoding stage with adjustable coding rate through Rate Matching, a constellation mapping stage, and a physical resources mapping stage (Fig. 1a). The FEC encoding step is assumed to split the packet into N codeblocks, each of them being assigned the same MCS value according to the reported CQIs. The resource mapping stage maps constellation symbols into resource elements following a vertical direction in the time-frequency diagram (as illustrated in Fig. 2a). Constellation symbols corresponding to each codeblock are therefore spread over the whole user bandwidth for improved diversity. The received block, as a result of the channel's frequency selectivity, will exhibit significantly different post-detection SINR values at each of the constituent codeblocks. Standard LA is then based on a single MCS value to be chosen so as to ensure a given block error rate (BLER) at reception.

As an alternative approach, let us assume an OFDM transmitter where MCS selection is made dependent on the actual channel conditions experienced by each codeblock (Fig. 1b). A set of codeblock sizes $\{CBS_1, \ldots, CBS_C\}$ and modulations $\{MOD_1, \ldots, MOD_C\}$ can then be selected prior to each transmission, where C is the number of constituent codeblocks. Constellation symbols are then mapped into resources following a first-horizontal-then-vertical direction in the time-frequency diagram (Fig. 2b), in such a way that the actually selected modulations and coding rates will match more closely the frequency-domain channel variations experienced by the codeblocks. The selection of codeblock sizes and modulations by the transmitter will assume perfect knowledge of the post-detection SINR values at the receive side, either estimated (in the uplink) or reported by the users (in the downlink). This mechanism will be referred to as frequency-dependent link adaptation (FDLA).

Codeblock sizes should be picked from a set of possibilities allowed by the FEC encoding stage. By exploiting the higher granularity provided by the known SINR values, it is possible to fine-tune the coding rates and hence the amount of information conveyed by each codeblock. After FEC encoding, the sizes of the encoded codeblocks will be equal to the input codeblock sizes divided by the selected coding rates. For simplicity, in what follows all encoded codeblocks will involve the same number of resource elements, equal to the available resources divided by the number of codeblocks. If we denote CBS_i as the size of the i-th codeblock prior to encoding, then $CBS_i = (N_{RE}/C)\cdot M_i \cdot r_i$ where N_{RE} is the number of available data resource elements, and M_i and r_i are the modulation order and coding rate of the i-th codeblock, respectively. Codeblock sizes and modulations can be

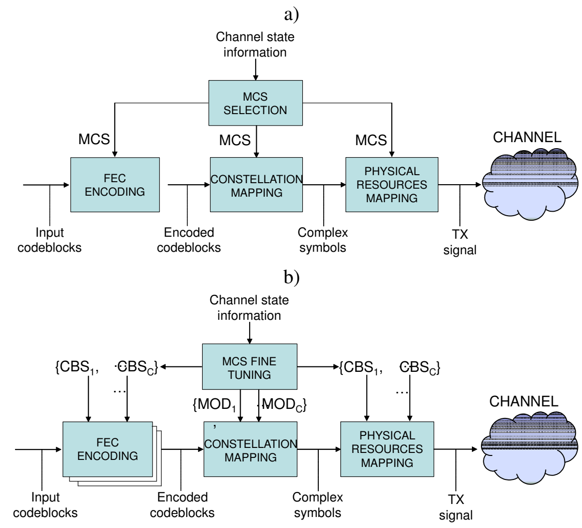

Fig. 1. Comparison between: (a) standard LTE transmitter architecture with a single MCS value for all the input codeblocks; (b) proposed OFDM transmitter with different allowed codeblock sizes $\{CBS_1, \ldots, CBS_C\}$ and modulations $\{MOD_1, \ldots, MOD_C\}$.

efficiently communicated to the receiver by means of in-band signaling, as will be described in Section III.

Figure 3a illustrates how codeblocks after FEC encoding uniformly extend over the N_{RE} resource elements allocated to the user, while the amount of information conveyed by each codeblock can be made dependent on the SINR values. As will be discussed in section IV, this "direct mapping" of codeblock formats to SINR values may lack the extra frequency diversity provided by standard resource mapping, depending on the range of frequencies occupied by the encoded codeblocks. As an alternative, Fig. 3b illustrates a "diversity mapping" scheme

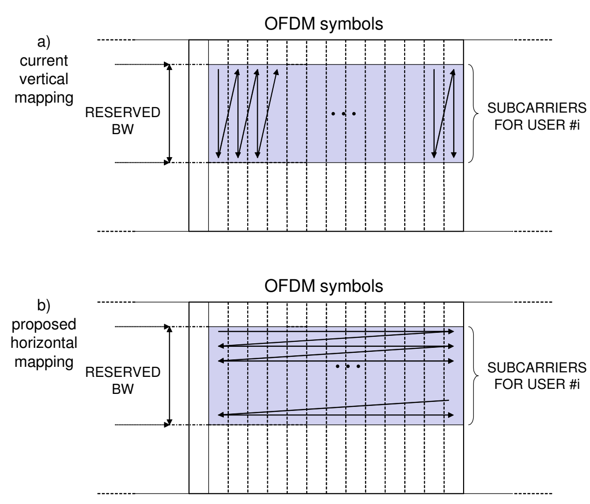

Fig. 2. Comparison between: (a) resource mapping mechanism in standard LTE, following resource assignments in vertical directions; and (b) proposed resource mapping operation following horizontal directions.

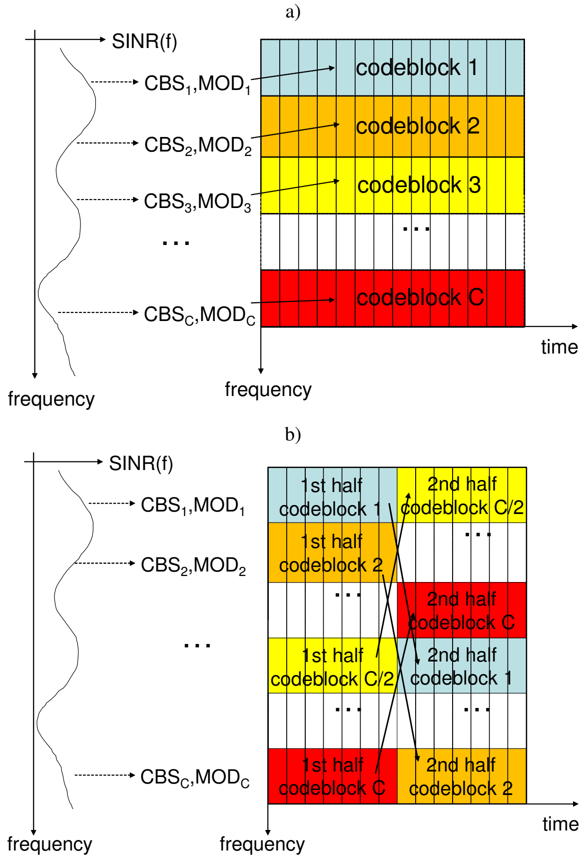

Fig. 3. Illustration of the encoded codeblocks in the frequency domain: (a) "direct mapping"; (b) "diversity mapping".

whereby the second half of each codeblock undergoes a frequency shift of $N_{RE}/2$ subcarriers when mapping to resources in the second slot. This frequency shift may improve diversity in channels whose coherence bandwidth is larger than the frequency range occupied by the encoded codeblocks.

The modulations and coding rates can be suitably obtained from the set of post-detection SINR values $\{\gamma_n\}$ corresponding to the allocated subcarriers [5], which are assumed to be ideally known at the transmitter side. Post-detection SINR values characterize the received signal quality after the equalization stage, and can be exploited by appropriate L2S techniques. Such techniques provide an effective SINR value that yields the same BLER as the system would have in Additive White Gaussian Noise (AWGN) conditions, through the definition of a suitable mapping function [3]

$$I\left(\frac{\gamma_{eff}}{\alpha_1}\right)=\frac{1}{L}\sum_{k=0}^{L-1} I\left(\frac{\gamma_k}{\alpha_2}\right). \quad (1)$$

In the above expression, γ_{eff} is the effective SINR, I is the mapping function, L is the number of SINR samples, and α_1,α_2 are parameters that must be optimized for minimum squared error between the predicted BLER and the real obtained BLER [3]. α_1,α_2 are in general dependent on the MCS and the occupied bandwidth, and should be reported by the devices e.g. as part of the device capabilities report.

Mutual Information Effective SINR Mapping (MIESM) is the mapping function used in this study, where I is the bit-level Mutual Information (MIB) function trained over a bandwidth of 8 Resource Blocks (RB) [3]. Effective SINR values are obtained and, from them, CQI values characterizing the individual codeblocks ($CQI_i, i=0,\ldots,C-1$), as well as the wideband CQI (CQI_{avg}). CQI_i values are calculated so as not to exceed a codeblock BLER ($BLER_i$) given by the expression $(1-BLER_i)^C=1-0.1$, hence leading to 10% overall BLER. Codeblock sizes are then calculated according to:

$$\overline{CBS_i}=CBS_i\times\frac{TrBlk(CQI_i)}{TrBlk(CQI_{avg})}, i=0,\ldots,C-1, \quad (2)$$

where $\overline{CBS_i}$ is the proposed i-th codeblock size, CBS_i is the standard LTE i-th codeblock size, $TrBlk(CQI_i)$ is the transport block size that would correspond to CQI_i, and $TrBlk(CQI_{avg})$ is the transport block size that would correspond to CQI_{avg}. The values $\overline{CBS_i}$ are further adjusted so as to match the nearest codeblock size allowed by the LTE Turbo encoder [4]. The higher granularity provided by the codeblock-dependent CQI_i values, as opposed to subband-dependent CQIs, allows better match of codeblocks to channel responses under the constraints set by the SINR accuracy. Codeblock-dependent modulations are also selected according to CQI_i.

According to (2), codeblock sizes are modified with respect to the standard size as a result of the codeblock-dependent effective SINRs. If a codeblock size exceeds the maximum of 6144 bits, the number of codeblocks is increased by one (up to a maximum of 13 codeblocks), and calculations are repeated again for all the codeblocks so as to fine-tune again the sizes. This procedure ensures optimum adaptation of codeblock sizes to channel responses.

After the above procedure, the transmitter checks whether the resulting transport block size is greater than the one in standard LA. If it is not the case, the transmitter switches to standard LTE LA for that subframe; otherwise FDLA is employed. Such dynamic switching between standard LA and FDLA is interesting because not always the proposed procedure should yield better results than the standard one. For example, user mobility can lead to outdated channel state information when trying to match codeblock sizes to SINR values. Similarly, channel coherence bandwidths which are much smaller than the frequency ranges occupied by the encoded codeblocks can lead to little or no gains when employing FDLA: strong SINR fluctuations will favor the reliance on *average* modulation and coding schemes, rather than frequency-dependent ones, just as standard LTE does. Hence the algorithm switches to a standard approach whenever there is no expected throughput gain from the proposed approach, on a subframe basis.

Reporting of SINR values for downlink LA need not have high granularity: granularities similar to those in CQI subband feedback (with one SINR value for several RBs) may be sufficient for FDLA. Ideal SINR values at the transmitter side are however considered in this paper.

So far the described LA mechanism can be regarded as an *inner loop* LA, whereby link adaptation blindly relies on the SINR values that are available at the transmitter. The presence of user mobility, along with the delay in channel reporting feedback, introduces additional impairments that should be tackled by an *outer loop* LA mechanism [7]. Such outer loop would aim at achieving a given BLER target for the first transmission, e.g. by introducing an offset A that biases SINR measurements or CQI values prior to obtaining codeblock formats [2], [7]. This paper however intentionally excludes outer loop from the analysis, so as to study the impact of the proposed inner loop FDLA mechanism without any further considerations. For this reason, only static UEs are studied in order to avoid channel aging effects.

III. In-band Signaling of Frequency-Dependent Modulations and Codeblock Sizes

A Modulation and Codeblock Size index (denoted as MCBS, not to be confused with MCS) is defined hereafter, comprising a Modulation field followed by a Codeblock size field (in any digital format). Codeblock sizes can be signaled by means of an index pointing to a table of allowed input sizes [4] (from 1 to 188 in LTE). Exploiting the fact that small variations of MCBS are usually observed in typical radio channels with sufficiently large channel coherence bandwidths, differential indications $\Delta MCBS_i$ may be given by subtraction of MCBS from the value obtained by standard procedures.

$\Delta MCBS_i$ values can be further encoded and constellation-mapped to resource elements. If an encoded $\Delta MCBS_i$ indication comprises d constellation symbols, the complete control message will yield a total of $C{\cdot}d$ symbols which can be efficiently spread throughout the time-frequency resources reserved for the user, in order to improve frequency diversity (Fig. 4). The expected overhead from such control signaling can be considered negligible as codeblocks with hundreds to thousands of bits will easily accommodate a few tens of control bits conveniently spread in the time-frequency resources. Errors in the detected $\Delta MCBS_i$ values would lead to erroneous detection and hence strong coding of MCBS is assumed.

IV. Simulation Results and Discussion

In order to assess the benefits of the proposed FDLA mechanism, results are obtained in an LTE downlink link-level simulator under the assumptions stated in Table I. A total of 100 static channel snapshots are randomly generated per SNR value, in static conditions (0 km/h), with SNR ranging from 0 to 24 dB (in 3-dB steps), and for 3GPP EPA and ITU IndoorA channel models. Throughput values are collected after 5000 received transport blocks for each SNR and channel snapshot. Post-detection SINR values are assumed to be perfectly

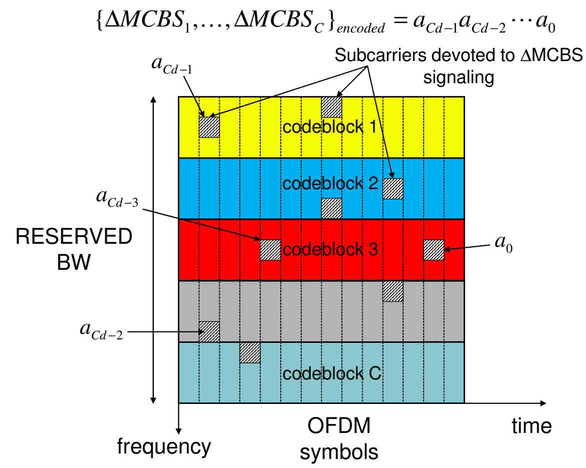

Fig. 4. An in-band signaling scheme to convey modulation and size indications for the codeblocks. Mapping of payload data to physical resources would have to skip the described resource elements devoted to codeblock signaling.

available at the transmitter side. Inner loop LA is based on MIESM L2S model, previously trained in the downlink of LTE over a user bandwidth of 8 RBs. Neither outer loop LA nor HARQ are considered: both are purposely excluded from the simulations so as to isolate the impact of the proposed FDLA mechanism when compared to standard LA. Both direct mapping and diversity mapping are studied in FDLA.

Effective SINR values are obtained over the whole user bandwidth (for standard LA) and over the frequencies occupied by the encoded codeblocks (for FDLA). Further mapping to AWGN BLER is performed by means of static tables, from which the optimum CQI not exceeding 10% BLER can be selected in each case. Table II contains the parameters α_1, α_2 of the trained MIESM model as defined in (1), along with the logarithmic mean squared error (MSE) through the expression:

$$MSE = \frac{1}{M}\sum_{i=1}^{M}\left(\log(BLER_e) - \log(BLER_s)\right)^2, \qquad (3)$$

where M is the number of channel realizations used to train the model (also shown in the table), $BLER_e$ is the estimated BLER, and $BLER_s$ is the real BLER.

The net throughput is obtained by discarding packets with errors from the overall throughput calculation. Figure 5 illustrates the percentage of subframes using the proposed FDLA mechanism, together with the increase in median throughput obtained in FDLA subframes. It can be seen that the median throughput increase is moderate in all cases, and tends to vanish at high SNR. This is expected as codeblock sizes and modulations do saturate at high SNR values, thus making channel variations more and more irrelevant for the selection of transport formats. Some performance improvement can however be observed at low to moderate SNR, with a percentage of FDLA subframes reaching its peak between 10 and 15 dB.

TABLE I. SIMULATION ASSUMPTIONS

Parameter	Setting
Carrier frequency	2.6 GHz
User Bandwidth	20 MHz (100 RB)
Channel types	3GPP Extended Pedestrian A and ITU Indoor Office A, 0 km/h
Detector type	SISO MMSE, downlink
SNR	0 dB to 24 dB in 3-dB steps
No. blocks and channel snapshots	100 snapshots per SNR value; 5000 blocks per snapshot
Link-to-System model	MIESM trained over 8 RBs in the downlink
CSI at the transmitter	Ideally known post-detection SINR
Channel estimation	Ideal
Inner loop LA	MIESM-based, over the user bandwidth or the subcarriers occupied by each codeblock
Outer loop LA	Not present
HARQ retransmissions	Not present
Mapping in FDLA	Direct mapping and diversity mapping

TABLE II. MIESM PARAMETERS OVER 8 RBS: TRAINED PARAMETERS, MEAN SQUARED ERROR, AND NUMBER OF CHANNEL REALIZATIONS

CQI	α_1	α_2	MSE	M
1	0,531155779	0,531155779	0,002989733	370
2	2,81278419	2,812997289	0,001467561	259
3	2,60931286	2,626278213	0,018865555	249
4	1,015822997	1,017391767	0,005546104	182
5	1,107439847	1,10985894	0,001965328	136
6	1,022012251	1,020423244	0,00635935	184
7	0,554612779	0,557105671	0,006057602	181
8	0,650072987	0,654547125	0,012932865	140
9	0,726092611	0,725332077	0,021756532	114
10	0,811366653	0,80706628	0,005399499	122
11	0,783643704	0,792563449	0,003624075	110
12	0,933191027	0,93664777	0,005978405	122
13	1,004792821	1,006271415	0,007999028	104
14	0,989410025	0,974602018	0,032192243	142
15	0,937071551	0,963738988	0,024219935	150

Direct mapping yields higher throughput improvement than diversity mapping at low SNR values. The small number of encoded codeblocks in this case forces them to span over a wide frequency range, thus making diversity mapping more similar to standard LA. The percentage of FDLA subframes in diversity mapping is also lower than in direct mapping (28% vs. 52% peak values, respectively), as the former resembles standard LA more closely than the latter, hence leading to lower chances of being advantageous. Performance improvements are virtually identical in EPA and IndoorA channels with diversity mapping, something which can be highly desirable in practical realizations.

The distribution of instantaneous throughput improvements, at subframe level, can provide more insight than the simple median throughput improvements. Figure 6

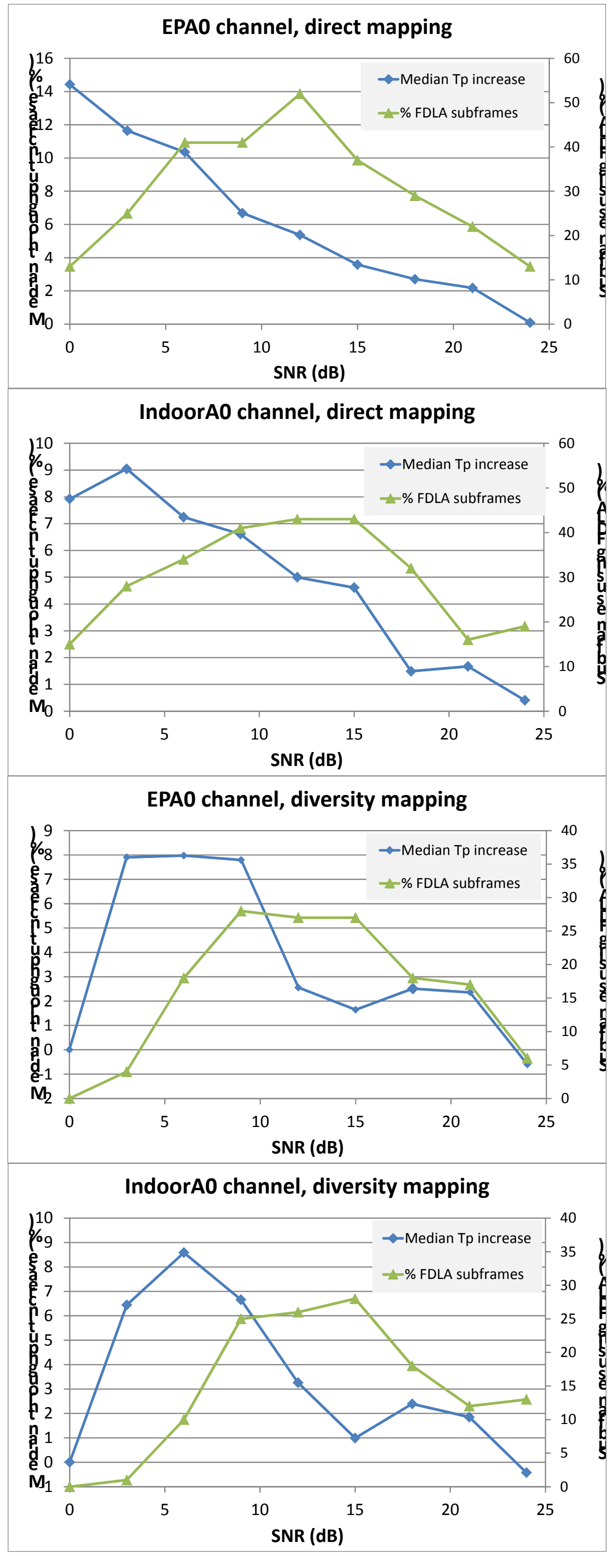

Fig. 5. Median throughput increase (blue curve) and percentage of subframes employing FDLA (green curve), in direct mapping and diversity mapping, for both EPA0 and IndoorA0 channel models.

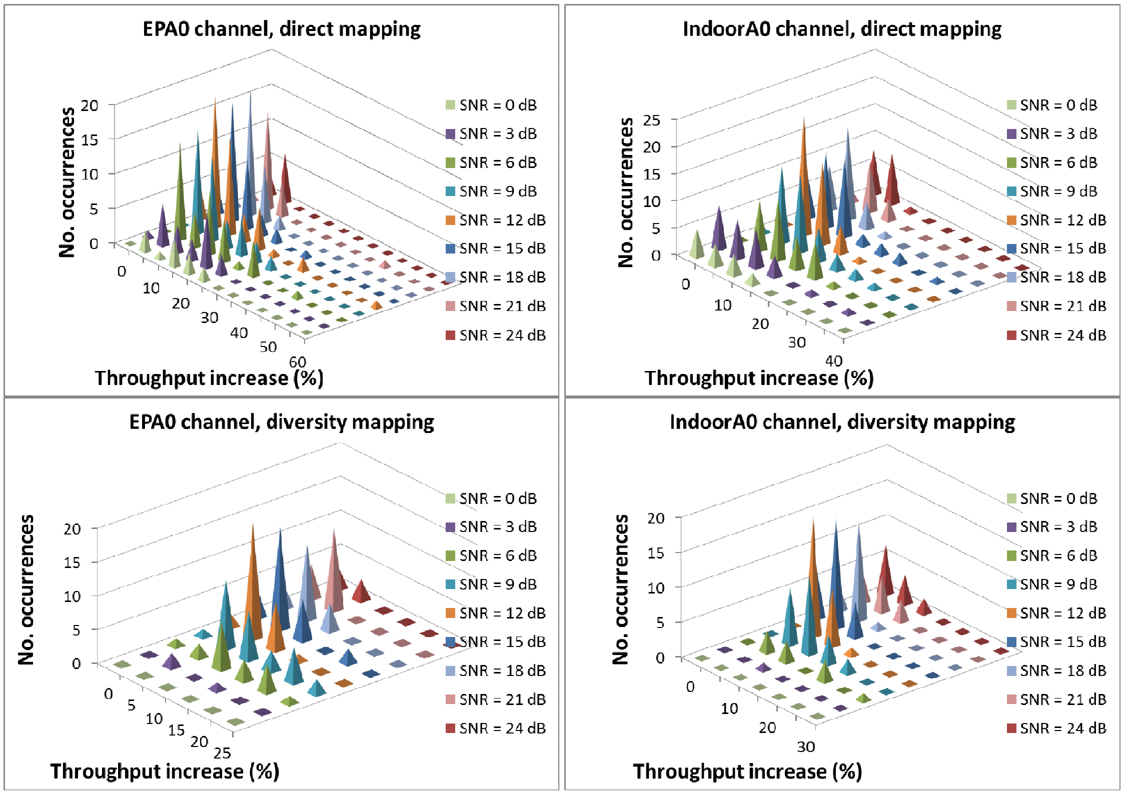

Fig. 6. Histograms showing the relative increase in instantaneous throughput for subframes employing FDLA, with EPA0, IndoorA0 channel models and both direct mapping and diversity mapping. It is to note the strong dependency of the distributions with SNR.

illustrates such distribution at FDLA subframes for both channel models and mapping procedures. It is to note the strong dependency of throughput improvements on the SNR, with little or no improvements at SNR = 0 dB and SNR = 24 dB, and quite significant throughput increases in between. In particular, subframes with more than 30% throughput improvement can be easily observed between 6 and 18 dB. The highest throughput gains are observed in EPA channel with direct mapping FDLA, where particular subframes reach throughput improvements as large as 60% at SNR = 12 dB. This is expected given the channel coherence bandwidth (25.8 RB for 50% correlation [6]), larger than the bandwidth occupied by the encoded codeblocks but still smaller than the user's bandwidth, which makes direct mapping really suitable. Diversity mapping yields almost identical results in EPA and IndoorA channel models. At high SNRs FDLA becomes impractical because of the saturation in the codeblock sizes.

V. Conclusions

This paper proposes a frequency-dependent link adaptation mechanism by which codeblocks are assigned individual modulation and coding schemes for better link adaptation. The proposed FDLA makes it possible to fine-tune the codeblock formats thus leading to throughput improvements over a wide range of SNR values, when measured in static conditions. Best results are obtained for FDLA direct mapping in EPA channel, while FDLA diversity mapping performs almost independently of the actual channel model. Further studies will be conducted in order to assess the impact of mobility on the proposed scheme, as well as the design of outer loop LA mechanisms able to cope with channel aging effects.

References

[1] 3GPP TS 36.213, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures".

[2] K. Aho, O. Alanen, and J. Kaikkonen, "CQI Reporting Imperfections and their Consequences in LTE Networks", the 10th IARIA International Conference on Networks (ICN) 2011, January 23-28, 2011.

[3] J. Olmos, S. Ruiz, M. García-Lozano and D. Martín-Sacristán, "Link Abstraction Models based on Mutual Information for LTE Downlink", COST 2100 TD(10)11052, 2-4 June, 2010, Aalborg (Denmark).

[4] 3GPP TS 36.212, "Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding".

[5] E. Ohlmer and G. Fettweis, "Linear and Non-Linear Detection for MIMO-OFDM Systems with Linear Precoding and Spatial Correlation", IEEE Wireless Communications and Networking Conference (WCNC) 2010, April 18-21, 2010, Sydney (Australia).

[6] S. Andreev, A. Larmo, M. Gerasimenko, V. Petrov, O. Galinina, T. Tirronen, J. Torsner, and Y. Koucheryavy, "Efficient Small Data Access for Machine-Type Communications in LTE", IEEE International Conference on Communications (ICC), 2013.

[7] A. Duran, M. Toril, F. Ruiz, A. Mendo, "Self-Optimization Algorithm for Outer Loop Link Adaptation in LTE", IEEE Communications Letters, vol. 19 (11), pp. 2005-2008, Nov. 2015.